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FREEZE-THAW DURABILITY OF RUBBERIZED SEGMENTAL RETAINING WALL UNITS

Gheni, Ahmed[1]; ElGawady, Mohamed[2]; Nain, Monika[3] and Thompson, Jason[4]

ABSTRACT

This work proposed utilizing crumb rubber as a partial aggregate replacement to provide eco-friendly alternative segmental retaining wall units with enhanced freeze-thaw durability. After an investigation to determine the optimum size and replacement ratio of the crumb rubber, the fine aggregate was replaced with comparable sizes of rubber particles in three volume percentages of 5%, 10%, and 15% producing rubberized segmental retaining wall (RSRW) units in a manufacturing plant and the laboratory of Missouri University of Science and Technology. ASTM C666/C666M and ASTM C1262/C1262M standard tests were utilized to examine the freeze-thaw durability of the produced units, where the tested specimens were subjected to full-water submergence and partial submergence. The results indicated an optimum rubber ratio of 5%, which resulted in higher compressive strength and lower water absorption than that in the conventional SRWs. Also, the freeze-thaw durability according to both tests was significantly improved after incorporating the rubber particles. Results from ASTM C666/C666M test showed that replacing the fine aggregate with 5% and 15% of rubber reduced the average accumulated weight loss from 20% to 2.6% after 150 freeze-thaw cycles which represented a 93% increase in durability. Besides, specimens with 5% rubber were able to reach 240 freeze-thaw cycles before collapse compared to only 120 cycles for the conventional SRWs. A similar trend was reported from the ASTM C1262 /C1262M test, where the average accumulated weight loss was reduced from 0.2% to 0.13% and 0.15% after 140 freeze-thaw cycles which represented an increase of 35% and 25% in the durability for specimens with 5% and 15% rubber, respectively. The reason behind these improvements was attributed to the increase of the ultimate strain capacity of RSRWs which allowed the newly proposed materials to absorb higher freezing deformations.

KEYWORDS: *crumb rubber, durability, freeze-thaw, rubberized segmental retaining wall units*

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[1] Lecturer, Dept. Civil Engineering, Komar University of Science and Technology, Iraq, ahmed.gheni@komar.edu.iq
[2] Professor and Benavides Scholar, CArE Engineering, Missouri S&T, Rolla, MO, USA, elgawadym@mst.edu
[3] Engineering Projects Manager- Structural Hardscapes, NCMA, Herndon, Virginia, USA, mnain@ncma.org
[4] Vice President of Engineering, NCMA, Herndon, Virginia, USA, jthompson@ncma.org

INTRODUCTION

Construction activities were the largest consumer of natural materials in the U.S. during the last century. The U.S.A consumption of construction materials outpaces all other material. In 1998, mineral fine and coarse aggregate production reached 1,120 Tg representing 73% of all natural materials used by weight [1]. This raises serious concerns about the continuous depletion of these natural resources and exhaustion of the environment. Meanwhile, the world is facing a serious threat dealing with scrap tires, given the continuous increase in the number of vehicles, which is directly connected to the increase in the global population. According to the most recent statistics, there are more than 1.1 billion vehicles on the road, and this number is expected to double by 2040 [2]. This enormous number of vehicles across the world led to the global yearly production of 1.7 billion tires and caused an annual generation of 1.0 billion scrap tires [3], which results in increased environmental concerns regarding how to properly dispose of them.

Researchers have shown that crumb rubber, which comes from waste tires, can be used to replace mineral aggregate leading to more environmentally friendly construction practices [4-13]. Wet-cast rubberized concrete exhibited better freezing and thawing durability compared to conventional concrete mixtures [14-16]. Additionally, anti-sulfate corrosion was enhanced with the use of rubber in concrete [17-19]. Using crumb rubber helped to produce more durable concrete by enhancing the abrasion resistance, frost resistance, acid attack, and chloride ion penetration [16, 20-23]; however, the effect of rubber on carbonation resistance varied based on the rubber content [24-26].

More than 4.6 billion CMUs were produced in the U.S.A in 2014, a nearly 12% increase over the year before. However, CMUs are currently manufactured using conventional aggregates that are sourced from the environment. Replacing the natural fine aggregates with crumb rubber produced from scrap tires has the potential to increase freeze-thaw durability, reduce use of quarried aggregates, and repurpose a large waste stream. Very few studies investigated the effect of adding crumb rubber to masonry units as a replacement of natural aggregates, producing what is termed rubberized concrete masonry units (RCMUs). Both load-bearing and non-load-bearing rubberized masonry hollow blocks and bricks, where mineral aggregates were partially replaced with crumb rubber, were produced [27-29]. Previous researchers focused on finding a new home for recycled rubber while attempting to match the mechanical characterizations of conventional masonry units. However, this study utilized a different approach by attempting to employ the unique features of rubber to improve the mechanical and durability properties of masonry units to result in a high-performance material.

This study investigates the impact of utilizing recycled rubber particles within masonry matrixes on freeze-thaw durability. In addition to the mechanical characterization of RCMUs including unit weight, water absorption, and unit compressive strength, the impact of incorporating varied crumb rubber ratios on the resistance of RSRWs to rapid freezing and thawing was evaluated according to ASTM C666/C666M-15, side by side with the freeze-thaw durability of dry-cast segmental RSRW units according to ASTM C1262/C1262M-18.

RESEARCH SIGNIFICANCE

In addition to introducing eco-friendly masonry units by utilizing a solid waste material, this work addresses the pressing need from both the masonry industry and market to improve the freeze-thaw durability of different types of masonry units under different environmental conditions.

EXPERIMENTAL PROGRAM

The experimental part of this investigation started with optimizing many parameters within the masonry mixtures and the SRW units' production process by using a gyratory compactor (Figure 1) to reach the highest packing density of mixtures by varying the fine to coarse aggregate ratio, crumb rubber size and ratio, and the compaction pressure and vibration. At least the test for each parameter was conducted for nine times to ensure good repetability.

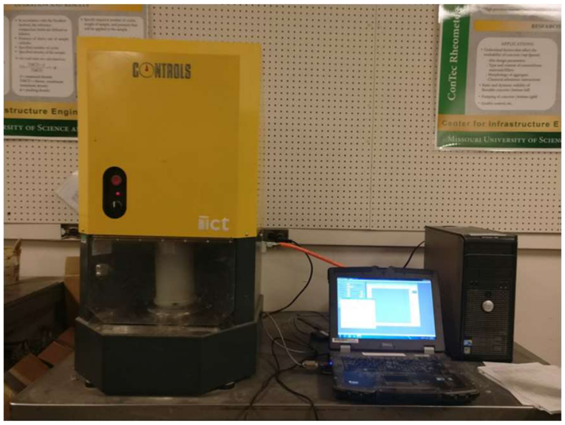
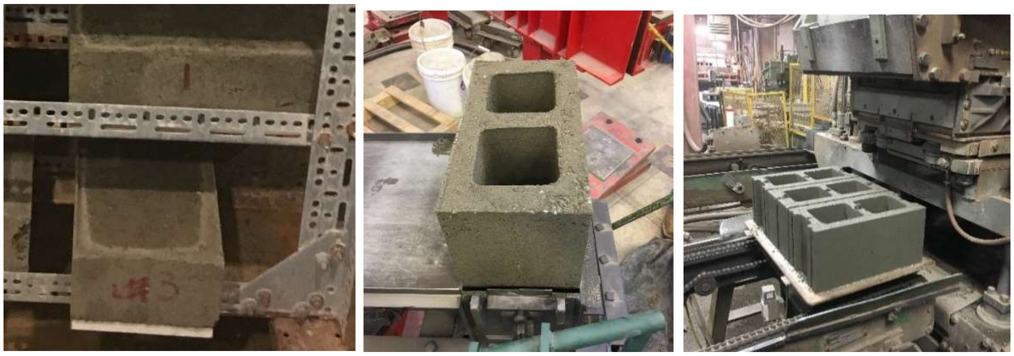


Figure 1: Gyratory Compactor for Determining the Packing Density of RSRW Mixtures

Using the optimum parameters, RSRW units (Figure 2a) and RCMUs (Figure 2b,c) with four rubber volume ratios of 0, 5, 10, and 15% were cast in both the lab (Figure 2a,b) and the masonry production plant (Figure 2c). It is worth mentioning that the conventional daily masonry production process was used without any modification, with a mix design as in Table 1.



(a) **(b)** **(c)**

Figure 2: Production of: a) RSRW units in the Lab b) RCMU in the Lab and c) RCMU in Masonry Production Plant.

Table 1: RSRW units and RCMUs Lab and Masonry Production Plant Mix Design (kg (*lb*)/ 3 units)

Material	0% Rubber	5% Rubber	10% Rubber	15% Rubber
Type I-II Portland Cement	6.92 (15.3)	6.93 (15.3)	15.3 (*6.92*)	6.92 (15.3)
Fly Ash	0.92 (2.03)	0.92 (2.03)	0.92 (2.03)	0.92 (2.03)
Masonry Sand	39.5 (87.7)	37.8 (83.3)	35.8 (78.9)	33.8 (74.6)
Washed Chat	24.08 (54.7)	24.8 (54.7)	24.8 (54.7)	24.8 (54.7)
Crumb Rubber	0.00 (*0.00*)	0.79 (1.75)	1.59 (3.51)	2.39 (5.26)
MasterCast 900 Additive	0.24 (0.52)	0.24 (0.52)	0.24 (0.52)	0.24 (0.52)
MasterPel 240 Additive	0.08 (0.18)	0.08 (0.18)	0.08 (0.18)	0.08 (0.18)

Physical Properties of RCMUs and RSRWs

After the curing period, the physical properties of RSRW units and RCMUs were examined through testing the unit weight (Figure 3a), water absorption (Figure 3b), and compressive strength (Figure 3c), according to ASTM C140/C140M−14b[30]. For each rubber content ratio, three individual RCMUs were tested for each test.

(a) (b) (c)

Figure 3: Physical Property Tests of RCMUs: a) Unit Weight, b) Water Absorption, and, c) Compressive Strength.

Freeze-thaw durability of RSRW units

The first test covers the resistance of RSRW units to rapid freezing and thawing according to ASTM C666/C666M-15, while the second one examined the freeze-thaw durability of dry-cast segmental RSRWs according to ASTM C1262/C1262M-18[31]. ASTM C666/C666M-15[32] is a standard test method focused on wet-cast concrete and not typically used for evaluating dry-cast (zero slump) concrete; whereas ASTM C1262/C1262M-18 specifically address the freeze-thaw durability of dry-cast SRW units. Using both procedures aimed to examine the freeze-thaw durability of RSRWs under two levels of freeze-thaw exposure.

Rapid Freezing and Thawing Testing per ASTM C666/C666M

This test was conducted according to ASTM C666/C666M Procedure A, which involves both freezing and thawing specimens while in full water submergence. Three specimens were tested for each ratio of rubber. The specimens were prepared by cutting 75x100x400 mm (3"x4"x16") prismatic pieces from the solid RSRW units (Figure 4a). Freezing and thawing tests began by placing the specimens in the thawing water at the beginning of the thawing phase. Then, the specimens went through cycles of freezing and thawing. After every 30 cycles, the specimens were removed from the apparatus in a thawed condition and the spalled residue form each specimen was weighed. Testing was continued for 300 freezing and thawing cycles or until full specimen damage, whichever occurred first. At the conclusion of this test, the amount of weight loss (an indication of a deterioration) was calculated by dividing the weight of accumulated residue by the calculated initial weight of the specimen as in Equation 3.

Rapid Freezing and Thawing Testing per ASTM C1262/C1262M

This test was performed according to ASTM C1262/C1262M-18, where five specimens were tested for each ratio of rubber under partial water submergence. The specimens were prepared by cutting a 100x200x38 mm (4"x8"x1.5") prismatic piece from the solid RSRW units (Figure 4b). The specimens were then placed in a container with the non-saw-cut surface facing down and water was introduced into the container to partially submerge the specimen. The specimens were frozen in a temperature-controlled freezer for 4 to 5 hr and thawed in the air for 2.5 to 96 hr, to ensure that all ice has thawed. After every 20 cycles, specimens were removed from the container and rinsed with water. All the rinse water was carefully collected in the container along with all loose particles from the specimen. For this purpose, the water was poured into previously weighed filter paper (W_f) to collect all residue from the test specimen. The filter paper with residue was dried (W_{f+r}), and the weight of the residue was calculated by subtracting the weight of filter paper. After completion of the freeze-thaw testing, specimens were oven-dried for at least 24 h; the final oven-dried weigh of specimen were recorded (W_{final}). The amount of weight loss (an indication of a deterioration) was calculated by dividing the weight of accumulated residue by the calculated initial weight of the specimen. The weight of residue and the weight loss of the specimen are given by the following equations:

$$W_r = W_{f+r} - W_f \tag{1}$$

$$W_{initial} = W_{final} - W_{residue} \tag{2}$$

$$W_{loss}\ (\%) = (W_{residue}/W_{initial}) \times 100 \tag{3}$$

where, W_r = weight of residue (spall); W_{f+r} = weight of the dried residue and filter paper; W_f = initial weight of the filter paper; $W_{initial}$ =calculated initial weight; W_{final} = final weight of specimen; $W_{residue}$ = total accumulated residue weight; and W_{loss} = weight loss of the specimen (%)

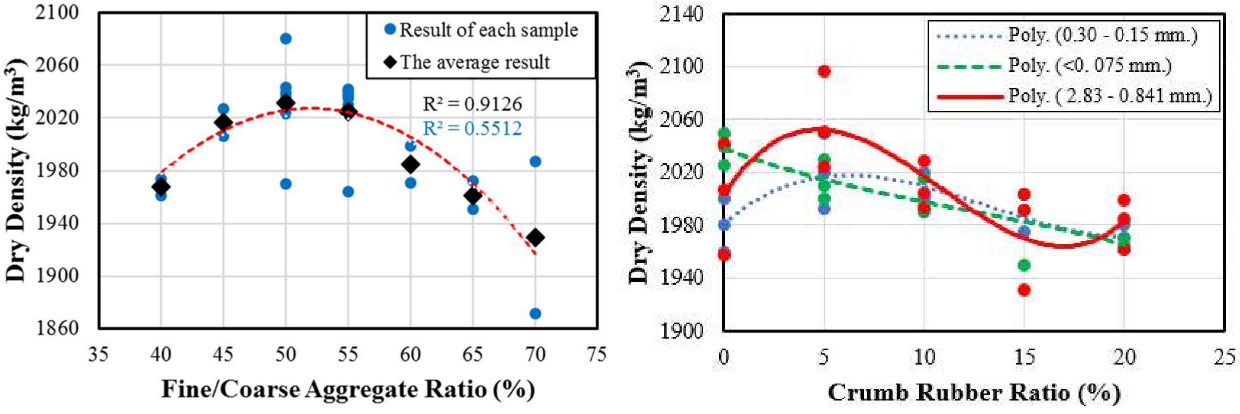
(a) (b)

Figure 4: RSRW Specimens For: a) ASTM C666/ C666M Test and b) ASTM C1262/ C1262M Test.

TEST RESULTS AND DISCUSSION

Optimization of mixtures and production parameters

In terms of the number of the gyratory cycles and the compaction pressure, the density reached its peak and remained approximately constant after 500 gyratory compaction cycles with a pressure of 0.21 MPa (30 psi). As a result, these values were adopted in the rest of this investigation. Figure 5a represents the dry density of RSRW mixtures with varied fine aggregate (sand) to coarse aggregate ratio. The figure shows that the ratio of the fine aggregate (sand) to coarse aggregate ratio of 50% produced the highest dry density compared to the other ratios under the pressure of 0.21 MPa (30 psi) and 500 gyratory cycles. Figure 5b shows the relation between the ratio of crumb rubber as a fine aggregate replacement and the dry density of the RSRW mixtures. As shown in the figure, replacing the fine aggregate with crumb rubber having a size of 0.841-2.83 mm resulted in the highest dry density compared to the other two crumb rubber sizes. Therefore, this size was adopted in the production of RSRW units for the rest of this project.



(a) (b)

Figure 5: The Relationship Between the Dry Density of RSRW Mixtures and: a) Fine-To-Coarse aggregate Ratio, and b) Rubber Particle Size.

Physical Properties of RSRW units

Table 2 presents the test result for the unit weight, water absorption, and compressive strength of the investigated RSRW units with varied rubber ratios according to ASTM C140/C140M−14b. Increasing the rubber content from 0 to 5% increased the oven-dry density slightly from 2167 to 2172 kg/m^3. The reason behind this increase was presented in the dry packing density results (Figure 5), where RSRW with 5% rubber gave the highest packing density of the dry raw materials compared to those with other rubber ratios as well as the reference conventional units without a rubber. However, increasing the rubber ratio from 5 to 15% decreased the oven-dry density from 2172 to 2077 kg/m^3, representing a reduction of 4.4% in the density. This reduction occurred because of the low packing density of the dry raw materials and the fact that the rubber particle's specific gravity was only 32% of that of the fine aggregate. Furthermore, the content of air voids increased with an increase in the rubber content in the mixture as indicated by the higher absorption rate (Table 2). RSRWs having up to 15% replacement of fine aggregate with crumb rubber had unit weights exceeding 2000 kg/m^3 and hence were classified as normal weight blocks.

Table 2. Physical Properties of RSRW units and RCMUs

Test type	Results	ASTM limits
Compressive strength ASTM C140/C140M	0% rubber 24.2 MPa 5% rubber 25.0 MPa 10% rubber 15.9 MPa 15% rubber 13.6 MPa	20.7 MPa (Min for SRW) ASTM C1372 13.1 MPa (Min for CMU) ASTM C90
Absorption testing ASTM C140/C140M	0% rubber 110 kg/m^3 5% rubber 107 kg/m^3 10% rubber 112 kg/m^3 15% rubber 125 kg/m^3	Lightweight: 288 kg/m^3 (Max) Medium weight: 240 kg/m^3 (Max) Normal weight: 208 kg/m^3 (Max)
Density classification ASTM C140/C140M	0% rubber 2167 kg/m^3 5% rubber 2172 kg/m^3 10% rubber 2120 kg/m^3 15% rubber 2077 kg/m^3	Lightweight: less than 1682 kg/m^3 Medium weight: 1682–2002 kg/m^3 Normal weight: 2002 kg/m^3 or more

Regarding the effect of the rubber ratio on the compressive strength of RSRW units, increasing the rubber content from 0% to 5% increased the compressive strength slightly from 24.2 to 25.0 MPa due to the previously reported increase in the packing density with the addition of 5% crumb rubber. However, increasing the rubber replacement ratio from 5% to 15% decreased the compressive strength nonlinearly by 46%. However, increasing rubber replacement from 10% to 15% decreased the compressive strength by 15% only. Despite this decrease in strength, the compressive strengths of all the investigated mixtures exceeded the minimum compressive strength required for load-bearing masonry units (CMU) according to ASTM C90-12 [33]required for structural applications, while only mixture with 5% rubber met the minimum requirements of Standard Specification for Dry-Cast Segmental Retaining Wall (SRW) Units, ASTM C1372[34].

Rapid freezing and thawing durability (ASTM C666/C666M)

As explained earlier, rapid freeze-thaw tests were conducted per ASTM C666/C666M- Procedure A. Figure 6 shows the relation between the number of freeze-thaw cycles according to ASTM C666/C666M- Procedure A and the cumulative weight loss due to these cycles. The behavior of RSRW after the rapid freeze-thaw cycles depended on the percentage of rubber content. The best performance was recorded with RSRW units having 5% rubber with only 2.6% weight loss after 150 cycles compared to 19.5% weight loss for the conventional SRWs after the same number of cycles. Specimens with a 15% rubber ratio behaved almost similar to that of 5%, however, specimens with 10% rubber showed the worst behavior compared to all other rubber ratios. This irregular durability behavior is attributed to serval contradicting factors including the increase in entrapped water, rubber crystallization, and internal spring as explained before in previous research [35]. This clarifies the vacillating behavior of the samples with a 5 and 10% rubber replacement ratio. The strength of RSRW units increased at the beginning of the low-temperature cycles when some of the rubber crystallized and the other part absorbed the internal stresses. When the entire amount of crumb rubber in the matrix crystallized, the flexibility of rubber decreased, which reduced its ability to absorb the internal stresses. Therefore, the strength started to decrease rapidly causing more internal and external damages, which leads to more losses in weight.

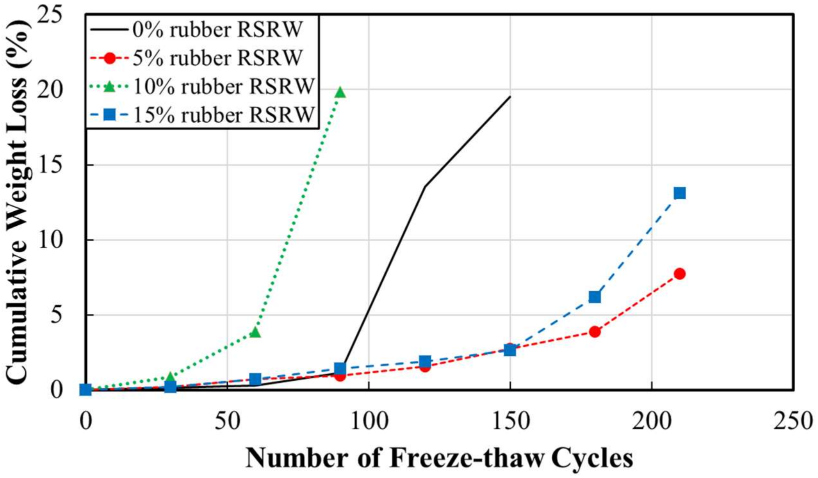


Figure 6: Cumulative Weight Loss vs Number of Freeze-thaw Cycles per ASTM C666/C666M.

Freeze-thaw durability of dry-cast segmental RSRWs (ASTM C1262/C1262M-18)

This part shows the results of freeze-thaw durability of dry-cast segmental RSRW units according to ASTM C1262/C1262M-18, which involves freezing in water and thawing in air. Figure 7 shows the relationship between the number of freeze-thaw cycles and the cumulative weight loss due to these cycles. The general trend of the weight loss was similar to that under the rapid freeze-thaw tests per ASTM C666/C666M- Procedure A, with a more noticeable effect of rubber where specimens with 5% and 15% rubber ratios behaved better than the conventional SRW units without rubber after 80, 100, 120, and 140 cycles, respectively. After 140 freeze-thaw cycles, the weight losses were 0.089% and 0.133% for specimens with a 5% rubber ratio compared to 0.194%

and 0.201% for conventional SRW specimens without any rubber at 120 and 140 cycles, respectively. However, this behavior was not linear from the beginning, where the conventional SRW units, up to 60 cycles, showed a similar performance to that with 5% rubber and better performance compared to RSRW units with 10 and 15% rubber. All specimens met the ASTM C1372 requirements of less than 1% weight loss after 100 cycles.

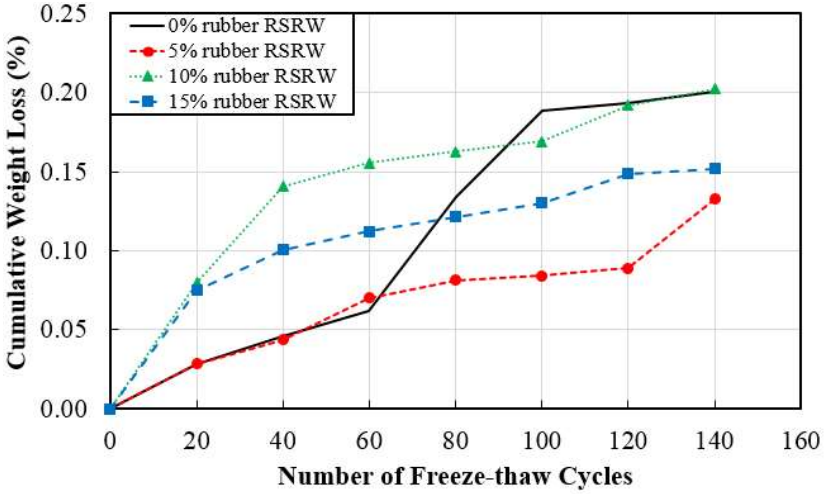


Figure 7: Cumulative Weight Loss vs Number of Freeze-thaw Cycles per ASTM C1262/C1262M.

FINDING AND CONCLUSIONS

This study investigates utilizing recycled crumb rubber as a partial replacement of natural mineral aggregate in the production of rubberized segmental retaining wall (RSRW) units as well as rubberized concrete masonry (RCMU) units. The project started with optimizing the production process, the size of rubber particles, and the rubber replacement ratios. Based on these parameters, eco-friendly rubberized units were produced both in the laboratory and in a plant setting. In addition to the physical properties of the new rubberized units, the impact of incorporating crumb rubber in RSRWs was examined using two different freeze/thaw test methods.

Based on the main findings of this study, the following conclusions can be drawn:

- In terms of the production process and parameters, this study discloses that:
  - Rubberized concrete masonry units with a crumb rubber replacement ratio of up to 15% can be produced in masonry production facilities using the exact conventional daily production process without any obstacles or modifications.
  - The compaction pressure of 0.21 MPa (30 psi) results in the highest dry density, which makes it recommended to be used in the mass production of RSRW units.
  - Replacing 5% of the volume of fine aggregate with recycled crumb rubber with particle size between 0.841 and 2.83 mm resulted in the highest dry packing density compared to other particle sizes.
- In terms of the physical properties of RSRW units, this study discloses that:

    - Crumb rubber replacement ratio of 5% resulted in the highest dry density, compressive strength as well as lowest water absorption. However, RCMUs with crumb rubber ratios up to 15% can be produced to meet the ASTM C90−12 requirements in terms of compressive strength, absorption, and density, while only the mixture with 5% rubber met the minimum strength requirements of the standard specification for dry-cast segmental retaining wall (SRW) units per ASTM C1372-17.
- In terms of the freeze-thaw durability of RSRWs, this study discloses that:
    - Under the rapid freeze-thaw tests per ASTM C666/C666M- Procedure A, incorporating rubber particles within the RSRW matrix had a positive impact on improving durability. The best performance was recorded with RSRW units having 5% rubber with only 2.6% weight loss after 150 cycles compared to 19.5% weight loss for the conventional SRW units after the same number of cycles.
    - A more pronounced positive effect of rubber was recorded under freeze-thaw durability of RSRWs according to ASTM C1262/C1262M-18. Specimens with 5% and 15% rubber ratios behaved better than the conventional SRW without any rubber after 80, 100, 120, 140 cycles, respectively.
    - All specimens with 0, 5, 10, and 15% rubber ratios met the ASTM C1372 freeze-thaw durability requirements of less than 1% weight loss after 100 cycles when tested per ASTM C1262/C1262M.

Based on the production process, physical properties, and the freeze-thaw durability result, it is recommended to replace 5% of the volume of fine aggregate with crumb rubber to produce both RSRW and RCMU units commercially.

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